Gravitational-wave Astronomy

Alexander Nitz
Max Planck Institute for Gravitational Physics - Albert Einstein Institute
On behalf of the
LIGO Scientific Collaboration
Both LIGO and the Virgo detectors were operational at the time of the signal - 12:41:04.4 UTC

GW170817 swept through the detectors’ sensitive band in ~100s ($f_{\text{start}} = 24$Hz)

Loudest (network SNR of 32.4), closest and best localized signal signal ever observed by LIGO/Virgo
GRB170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB170817A occurred this close in time and with location agreement by chance is 5.0x10^{-8} (Gaussian equivalent significance of 5.3σ)
GW170817 Story

- GW170817 was initially identified in LIGO-Hanford by a low latency binary-coalescence search
- A short instrumental noise transient ("glitch") appeared in LIGO-Livingston 1.1 seconds before the coalescence time
- Similar noise transients are registered roughly once every few hours in each of the LIGO detectors
  o no temporal correlation between the LIGO sites
- A rapid binary-coalescence re-analysis the LIGO and Virgo data (with the glitch suppressed) confirmed the presence of a significant coincidence! This led to the first HLV skymap
Rapid localisation - LIGO-Virgo: 31 deg$^2$

Rapid localisation - LIGO: 190 deg$^2$

Higher latency localisation - LIGO-Virgo: 28 deg$^2$

All numbers are quoted at 90% confidence

Position and distance to NGC 4993

Luminosity distance: $40^{+8}_{-14}$ Mpc

Multimessenger Observations

GW170817 - August 17, 2017 12:41:04 UTC

GW170817A - August 17, 2017 12:41:06 UTC

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB - August 17, 2017 13:21:42 UTC

LIGO-Virgo GCN reporting the first HLV skymap - August 17, 2017 17:54:51 UTC

Bright optical transient (SSS17a, now IAU identification AT2017gfo) discovered in NGC 4993 by One Meter, Two Hemisphere Team - August 18, 2017 01:05 UTC

Five other teams took images of the transient within an hour of the 1M2H image (and before the SSS17a announcement)

Approximately 70 ground- and space-based observatories followed-up on this event

The properties of gravitational-wave sources are inferred by matching the data with predicted waveforms.

For low orbital and gravitational-wave frequencies the evolution of the frequency is dominated by chirp mass.

As orbit shrinks the gravitational-wave phase is increasing influenced by relativistic effects related to the mass ratio.

Component masses are affected by the degeneracy between mass ratio and the aligned spin components $\chi_{1z}$ and $\chi_{2z}$.

\[ M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \]

- $|\chi| \leq 0.89$ limit imposed by available rapid waveform models
- $|\chi| \leq 0.05$ limit consistent with the observed population of BNS which will merge in Hubble time.
BNS properties

- The $\Lambda_1$ and $\Lambda_2$ parameters characterize the size of the tidally-induced mass deformations of each neutron star.
- Probability density for the tidal deformability parameters using the post-Newtonian model.
- Shaded gray - predictions for tidal deformability given by a set of representative equations of state (all of which support stars of $2.01 \, M_\odot$).
- Equations of state that produce less compact stars, such as MS1 and MS1b, predict $\Lambda$ values outside the 90% contour.

\[ \Lambda \sim k_2 (R/m)^5 \]

- $k_2$ - second Love number
- $R$ - stellar radius
- $m$ - mass of neutron star
GWs as standard sirens

\[ v_H = H_0 d \]

- \( v_H \) - local “Hubble flow” velocity of the source
- Use optical identification of the host galaxy NGC 4993

\[ H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

68.3% credible interval

Papers from LIGO-Virgo and partners


- B. P. Abbott et al., *Gravitational-wave Search for a Post-Merger Remnant of the Binary Neutron Star Merger GW170817*, available on papers.ligo.org

- B. P. Abbott et al., *Estimating the Contribution of Dynamical Ejecta in the Kilonova Associated with GW170817*, available on papers.ligo.org

- B. P. Abbott et al., *On the progenitor of binary neutron star merger GW170817*, available on papers.ligo.org

- B. P. Abbott et al., *GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Mergers*, available on papers.ligo.org
GW170814

The first GW signal observed by LIGO-Hanford, LIGO-Livingston and Virgo

The inclusion of Virgo means the sky localisation improves from 1160 deg$^2$ to 60 deg$^2$. 
GW170814

LIGO-Hanford and Livingston have similar orientations -> little information about GW polarizations

With Virgo in the network we can project the GW amplitude onto the 3 detectors -> learn about the nature of GW polarizations

General Relativity predicts metric perturbations possess 2 tensor degrees of freedom

Generic metric theories of gravity allow 6 independent modes - any combination of tensor (2-spin), vector (spin-1), scalar (spin-0) polarizations

Simple test of gravity - consider models where polarisation states are pure tensor, pure vector or pure scalar only

Purely tensor polarization is strongly favored over purely scalar or vector polarizations
Black Holes of Known Mass

Solar Masses

GW150914
LVT151012
GW170814
GW170104
GW151226

X-Ray Studies

LIGO/VIRGO
Masses in the Stellar Graveyard

in Solar Masses

LIGO Black Holes: 15

X-ray Binary Black Holes: 24

Known Neutron Stars: 68

LIGO Neutron Stars: 2

scale in log(10)
Rates of compact object mergers

Binary Black Hole Merger Rate
- Based on O1 BBH mergers: $9\text{--}240 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- Addition of GW170104, BBH merger rate: $12\text{--}213 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- Observation of GW170814 consistent with existing population

Binary Neutron Star Merger Rate
- Based on O1 non-detections: $< 12,600 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- Based on GW170817: $320\text{--}4740 \text{ Gpc}^{-3} \text{ yr}^{-1}$

Neutron Star - Black Hole Merger Rate
- Based on O1 non-detections (black hole mass $> 5 \text{ M}_\odot$)
- $< 3,600 \text{ Gpc}^{-3} \text{ yr}^{-1}$

So far we’ve only released some of our O2 results - so stay tuned!
More to come from O2

● Not all O2 results reported on.
● The Hanford-LIGO instrument can do significantly better
  ○ Laser beam motion caused excess noise
  ○ Currently this noise has been subtracted around the time of detections.
  ○ Work is underway to do so for the entirety of O2
Future Observing

[Diagram showing data for LIGO, Virgo, and KAGRA across different years and distance markers.]

From LIGO-P1200087-v42
Questions?